Benthic Oxygen Demand and Nutrient Fluxes in Budd Inlet

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Introduction

Knowledge of sedimentary processes is important in order to understand the dynamics of a water body because the sediments act as both a source and sink for organic and inorganic materials. In all water bodies, gravity acts on both organic and inorganic particulate material, and particulate material that is not advected out of an inlet or decomposed in the water column eventually settles to the sediments, where it is either permanently buried or remineralized. The deeper the inlet, the more time is available for settling material to be decomposed in the water column and the lower the amount reaching the sediments,and vice versa. Consequently, in shallow water bodies like Budd Inlet the sediments take on a quantitatively important role in organic matter and nutrient cycling.

Of primary importance to the health and productivity of a body of water are dissolved oxygen and inorganic nutrient concentrations. Sedimentary decomposition of organic matter removes oxygen from the overlying waters and recycles inorganic nutrients back into the water column (Berner, 1980). In particular, nitrogen is important because it is most often the nutrient limiting phytoplankton production in marine environments (Ryther and Dunstan, 1971). Nitrogen is also often introduced into coastal waters as a result of anthropogenic activities and frequently results in euthropication. Within the sediments, combined nitrogen (primarily NO_3, NH_4 and organic-N) is either remineralized and returned to the water column, i.e., recycled, or, under anoxic conditions, is denitrified to N_2 gas which diffuses out of the sediments and is ultimately lost to the atmosphere.

This study of sediment-water interactions was undertaken as part of an effort to evaluate alternatives for wastewater disposal in the area bordering Budd Inlet in southern Puget Sound. The overall objectives of the Budd Inlet sediment study were to:

1) measure the sediment oxygen consumption rate and determine its importance in regulating water column dissolved oxygen levels;
2) determine and understand the role of the sediments in nutrient cycling in the inlet, especially nitrogen cycling; and
3) support development of a dynamic sediment model to be used in conjunction with the water-column model to analyze development.

Methods

Benthic conditions were monitored over the course of a year at four locations throughout Budd Inlet in southern Puget Sound. Samples were collected approximately twice a month from September 1996 through September 1997. Locations of each station and approximate depths are shown in Figure 1. Station A was located in roughly 10 m of water in the dredged turning basin of the inner inlet, and was the closest station to Capitol Lake. Station B was the shallowest of the four stations, with a Mean Lower Low Water (MLLW) depth of two meters, and was the only station where the sediments and bottom water were within the euphotic zone. Station C was approximately 10 m deep and located more or less equidistant between the east and west boundaries of the inlet, as well as between the north and south boundaries of the inlet. Station D was about 15 m deep, closest to the mouth of the inlet, and thus closest to the rest of Puget Sound.

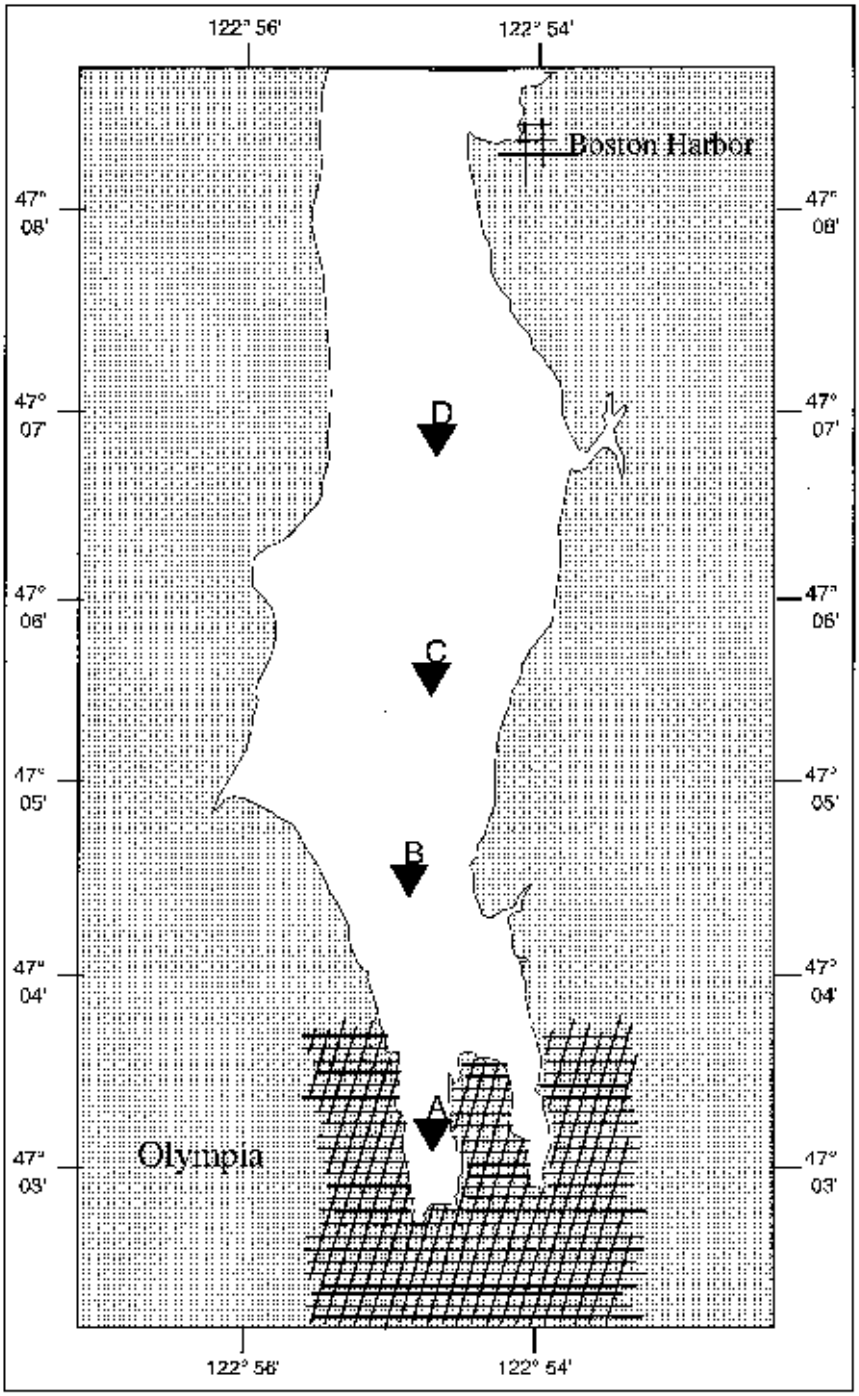

Figure 1. Benthic study station locations in Budd Inlet.

Samples for bottom water concentrations of dissolved oxygen and nitrogen gas, nitrate, ammonium, and silicate were taken using a Niskin bottle during each sampling period. Bottom water temperature and dissolved oxygen were measured using a SeaBird CTD.

In situ benthic chambers (mini-landers) described in Devol et al. (1997) were used to determine the exchange of solutes between the sediments and overlying water. The landers can be envisioned as "bell-jars" that sit on the sediments and enclose a volume of water overlying the sediments for some period of time. By sampling the overlying water as a function of time, benthic fluxes between the sediments and the overlying water can then be calculated. Mini-landers consisted of a stainless steel flux chamber with

an open bottom and a moveable top. With the top open, the mini-landers were implanted in the bottom sediments where the chamber enclosed a 412 cm^2 section of sediment and a volume of overlying water. Shortly after the mini-lander was placed on the sediment, the top of the chamber was closed, thus isolating the entrapped overlying water. At pre-programed times, spring-activated syringes extracted water from the closed box by drawing it through nylon tubing. Water volume inside the box was replaced by water drawn in through another nylon tube connected to the outside of the chamber. Calibrated 5-mL nylon loops were placed in-line between the chamber and the syringe samples and were used for dissolved gas analysis. A known amount of lithium chloride was injected into the box shortly after the lid was closed to calculate the exact volume of overlying water in the chamber, and to ensure that the chamber was free of leaks. Throughout the deployment, water inside the chamber was continuously stirred. All actions of the mini-lander were regulated by a preprogrammed microprocessor attached to the top of the instrument.

Samples were collected at four time-points over the course of each deployment (8–12 hr). After the mini-landers were recovered, all samples were kept on ice and brought to laboratories at the University of Washington where samples for dissolved oxygen and nitrogen were analyzed immediately by gas chromatography. Oxygen and nitrogen were stripped from the 5-mL sample loops with a helium carrier gas. Residual water vapor was removed in a Drierite column prior to the sample entering a Varian gas chromatograph containing a molecular sieve 5A column and Carle thermoconductivity detectors (Devol and Christensen, 1993). Dissolved gas measurements were standardized with air according to Grundmanis and Murray (1992). Water samples for nitrate, ammonium, and silicate were frozen and analyzed at a later date with a Technicon Autoanalyzer using the methods described in Whitledge et al. (1981).

Results

Bottom Water Data

The seasonal trends in bottom water oxygen and nutrient concentrations are shown in Figure 2. Seasonal cycles of oxygen were similar at Stations A, C, and D, where oxygen concentration increased from September to a maximum around March and remained approximately constant through April. In May dissolved oxygen began to decrease at these three stations reaching a minimum in August. Among these three stations this trend was most pronounced nearest the head of the inlet and became more attenuated with distance from the head. The summer minimum oxygen concentrations at Stations A, B, and C were 63, 113, and 197 μM respectively. The exception to this seasonal trend was Station B where oxygen concentrations increased from March to June and reached supersaturated values (up to 427 μM) in July and August.

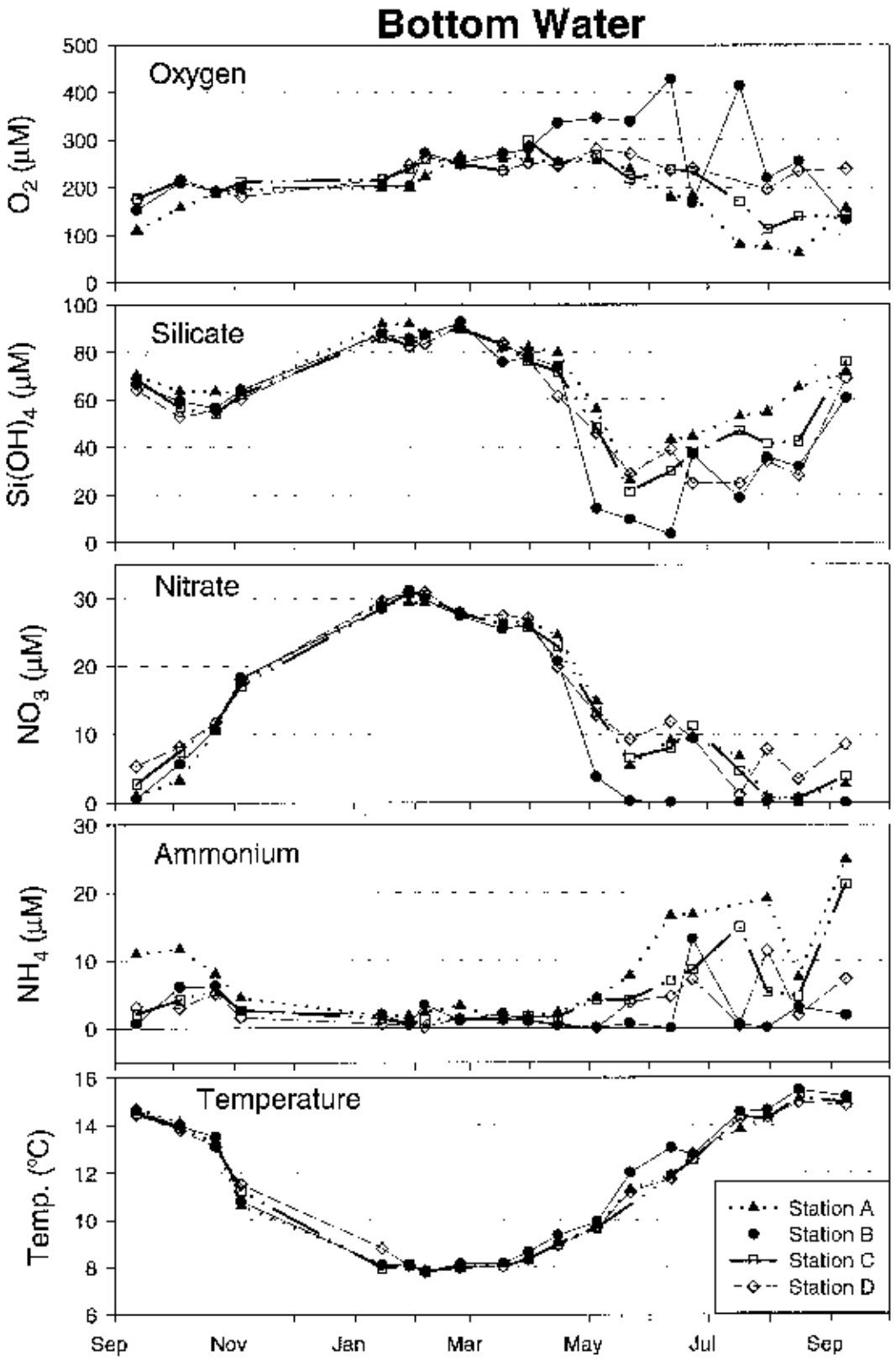

Figure 2. Bottom water temperature, oxygen, silicate, nitrate, and ammonium concentrations.

In September 1997, silicate bottom water concentrations were about 60 µM throughout the inlet. Concentrations at all stations then increased to a maximum of about 90 µM between November and March. With the onset of the spring phytoplankton bloom, silicate concentrations then decreased at all stations. Minimum values at Stations A, C, and D were all approximately 25 µM. Station B minimum silicate concentrations were lower than those at the other stations and approached zero in mid-June. After reaching their seasonal lows, concentrations at all stations began to increase again and returned to levels of ~75 µM by the end of the study.

Temporal trends in nitrate were also similar at all stations, increasing in the fall, reaching maximum values of about 30 öM in early February and then decreasing to summer minimum values near zero. Station B showed the most rapid spring decrease and nitrate was exhausted in early June, but such low levels were not encountered at the other stations until late July. Low nitrate concentrations were maintained at all stations throughout the summer and into fall.

Ammonium concentrations were consistently low during most of the year. However, during the summer, appreciable ammonium concentrations accumulated at all stations in the bottom water. Maximum concentrations of greater than 20 µM were observed at Station A, whereas at most other stations concentrations of about 5 µM were more common.

Temperature displayed the same temporal trend throughout the inlet, with more or less the same temperatures at A, C, and D. The trend at Station B, the shallowest station, was similar in shape and winter (Nov.–mid-March) temperatures were about the same as those at the other stations. Spring, summer and fall bottom water temperatures, however, were significantly warmer than those at the other stations. At all stations minimum temperatures of about 8_C were observed from February through mid-March after which time temperature increased to about 15_C in mid-August (Figure 2).

Flux Data

Benthic flux data were determined at each of the four stations for oxygen, silicate, nitrate, ammonium, and nitrogen gas. Oxygen and ammonium fluxes across the sediment-water interface at each station throughout the year are shown in Figure 3. All oxygen flux values were negative, indicating oxygen was taken up by the sediments from the overlying water, while all ammonium fluxes at each site were positive, signifying NH_4 release from the sediments into the overlying water. While values at each station varied, oxygen fluxes generally decreased during the winter months (November through February) at Stations A, B, and D, while oxygen fluxes at Station C were relatively low throughout this time period. Ammonium fluxes exhibited the same trend of decreasing throughout the winter at each station. At all sites, both oxygen and ammonium fluxes reached minima in early spring and then increased throughout the late spring and summer months. Oxygen flux data from Station A showed the greatest overall variation of the four stations, with a minimum rate of -5 mmoles O_2 m^{-2} d^{-1} in late March and a maximum rate of -35 mmoles O_2 m^{-2} d^{-1} in late July. Station A also had the greatest NH_4 flux (~13 mmoles N m^{-2} d^{-1}) in the late summer. Ammonium flux data from Stations A, B, and D all reached minimum values near zero in late March, while Station C had a slightly greater minimum NH_4 flux values of approximately 1.4 mmoles N m^{-2} d^{-1} on the same date.

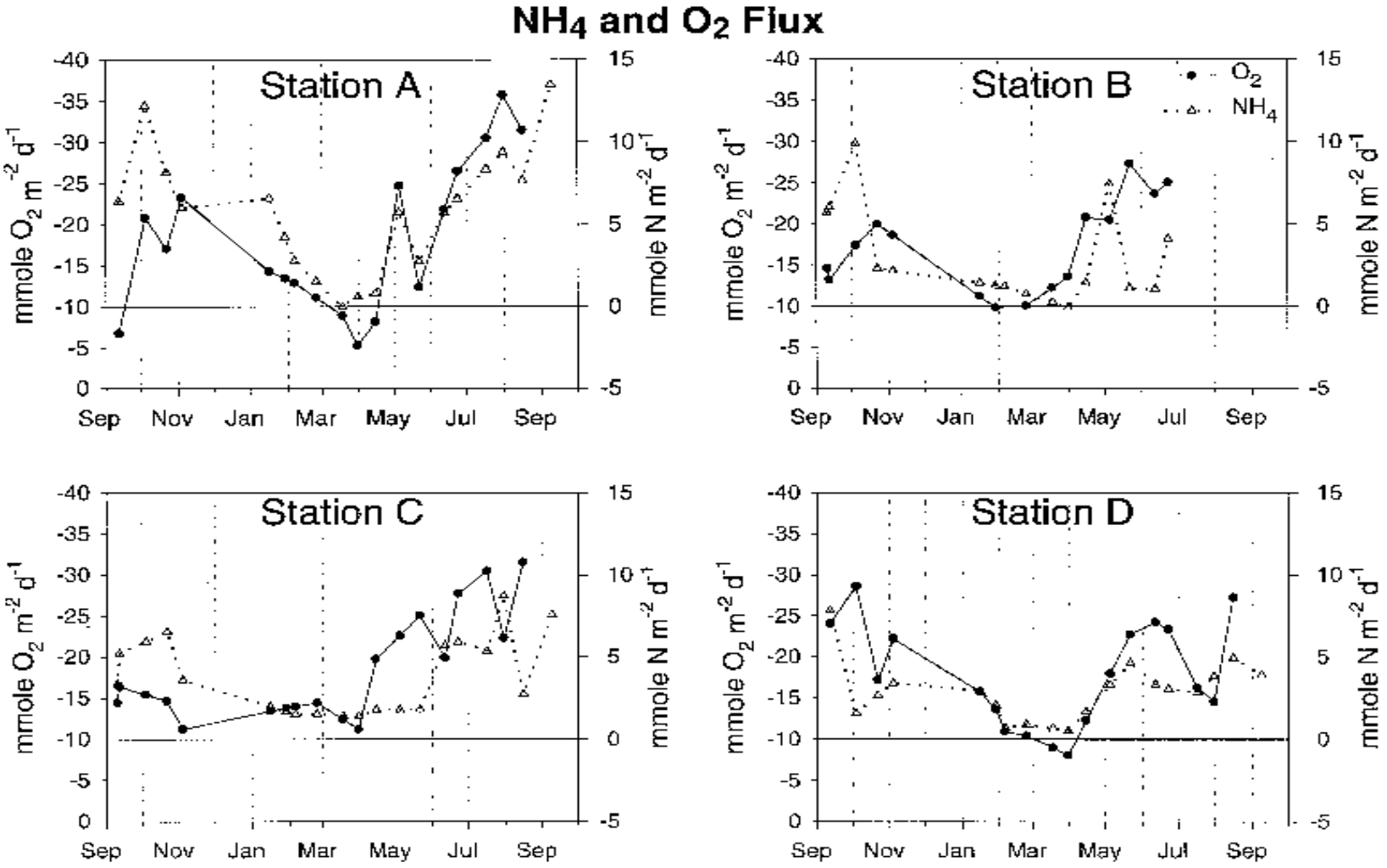

Figure 3. Seasonal ammonium and oxygen benthic fluxes in Budd Inlet. Oxygen fluxes are depicted by solid lines and symbols and are scaled on the left axis. Ammonium fluxes are depicted by dotted lines and open symbols and are scaled on the right axis.

Silicate fluxes (Figure 4) displayed similar annual trends at all stations. In all cases, $Si(OH)_4$ fluxes were from the sediments to the overlying water (positive values). In September values were between 5–10 mmoles Si m^{-2} d^{-1}, after which time they decreased at all stations until minimum rates were reached between late February and late March. Stations A, B and C had minimum $Si(OH)_4$ fluxes approaching zero. The minimum flux at Station D was approximately 3 mmoles Si m^{-2} d^{-1}. After reaching minima, fluxes out of the sediments at all stations then increased throughout the summer, and became variable in the early fall, with average values of about 15 mmoles Si.

With a few exceptions nitrate fluxes were generally low throughout the study period at all stations (<3 mmoles N m^{-2} d^{-1}) and fluxes were nearly always from the overlying water into the sediment. Fluxes were measurable by November when nitrate was present in the bottom waters, but fluxes were near zero during periods when bottom water nitrate was near zero (Figure 4).

Nitrogen gas flux data are more sparse than the other flux data, but generally averaged between 2 and 4 mmoles N_2 m^{-2} d^{-1}. The most complete record was obtained at Station C and showed a pattern similar to the other fluxes with relatively higher fluxes in the summer fall periods and generally low values during the winter.

Discussion

Annual trends in the bottom water oxygen, silicate, ammonium, and nitrate concentrations in Budd Inlet are dominated by the biogeochemical processes within the inlet and mixing with south Puget Sound waters across the mouth of the inlet. Thus, during the winter when both Budd Inlet and south Puget Sound are well mixed vertically and biological production is at a minimum, bottom water oxygen concentrations are near atmospheric equilibrium saturation, and the other dissolved species reflect the winter conditions in the main basin of south Puget Sound. Throughout the rest of the year the benthic study stations fall into two groups: deep stations (A, C, and D) having depths greater than the euphotic zone depth, and shallow stations (B) having bottom sediments within the euphotic zone. At the deep stations oxygen concentrations were near the saturation value in winter and as the spring bloom progressed beginning around March (J. Newton, personal communication) bottom water oxygen concentrations decreased due to organic matter decomposition of the settling plankton bloom in both the water column and the sediments. At the shallow stations, the trend was the opposite, with supersaturation of oxygen accompanying the bloom due to photo synthetic oxygen production within the euphotic zone. It is noteworthy that among the deep stations, the amount of oxygen depletion was greatest near the head of Budd Inlet and decreased toward the mouth, presumably resulting from progressively more influence of mixing with well-oxygenated south Puget Sound waters.

At all stations, both nitrate and silicate were removed from the bottom water as a result of the spring phytoplankton bloom. At the shallow station, the depletion was more rapid and more complete than at the other stations, with bottom water values approaching zero in May and June. This depletion at Station B probably resulted largely from processes taking place within Budd Inlet. Although the same trend of decreasing concentrations was observed at the deep stations, because these waters were below the euphotic zone, much of this was probably a reflection of seasonal processes taking place in south Puget Sound.

Ammonium is usually a transient form of nitrogen in marine environments. It is produced by the decomposition of organic matter and once formed it is either oxidized to nitrate by nitrifying bacteria or, if it is within the euphotic zone, it is taken up by phytoplankton as part of organic matter synthesis. The fact that is was present in the bottom water during the summer at all stations suggests a near-bottom source, and thus is likely the result of sedimentary decomposition of organic matter.

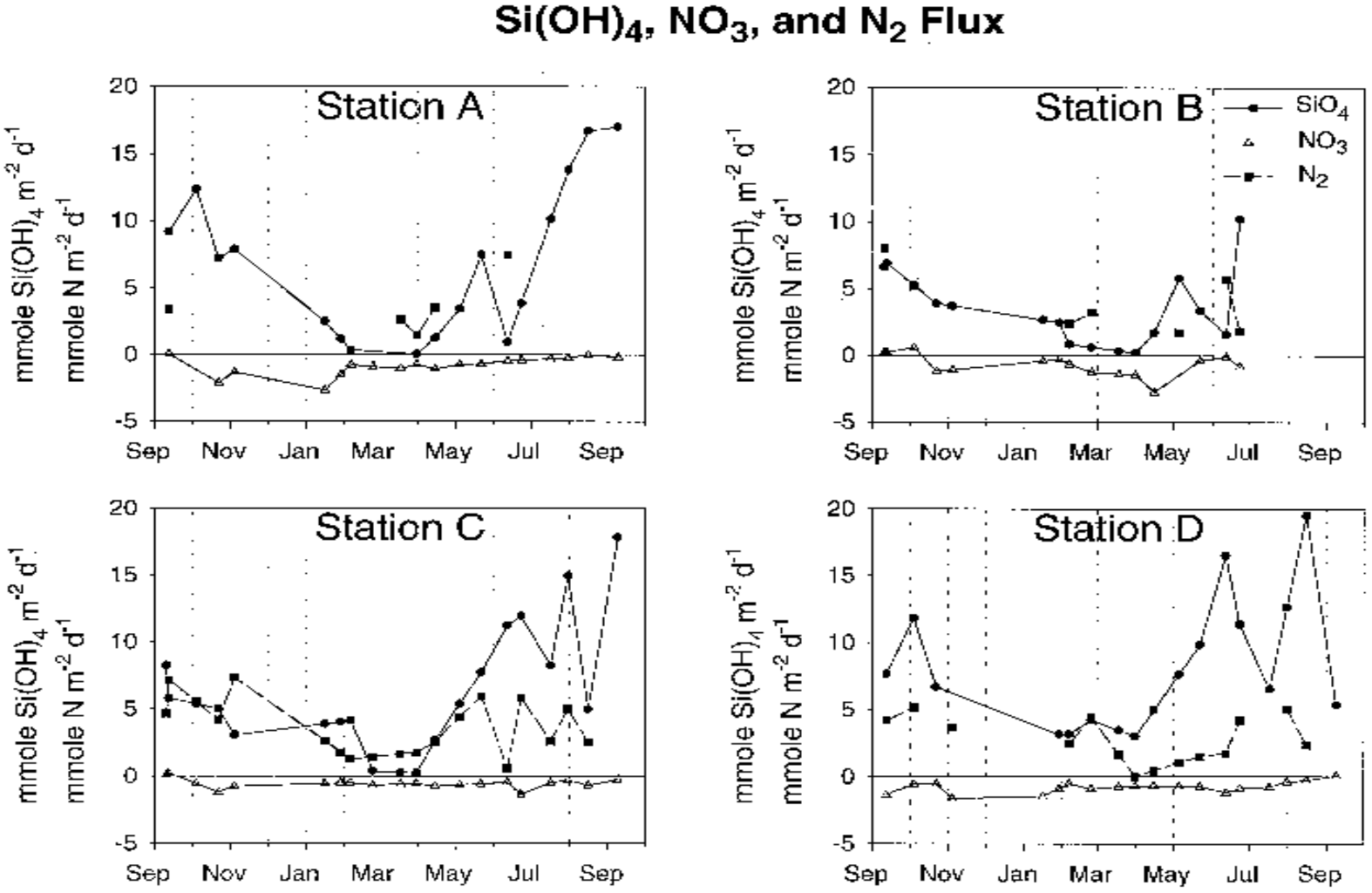

Figure 4. Seasonal silicate, nitrate, and nitrogen gas fluxes in Budd Inlet. Silicate fluxes are depicted by solid circles. Nitrate fluxes are depicted by open triangles. Nitrogen gas fluxes are depicted by solid squares.

Like bottom water nutrient concentrations, sediment fluxes also reflect seasonal cycles. Oxygen fluxes at each station increased in the spring and summer as the spring phytoplankton bloom progressed and new organic matter settled to the sediments. As productivity decreased in the fall and winter, less labile organic matter was transported to and decomposed in the sediments, which was reflected by the low oxygen fluxes during that time (Figure 3). The range in benthic oxygen fluxes in Budd Inlet was between about -5 and -35 mmoles O_2 m^{-2} d^{-1}. These values can be compared to values in Dabob Bay (Hood Canal) that were typically -3 to -8 mmoles O_2 m^{-2} d^{-1} with a maximum of -12 mmoles O_2 m^{-2} d^{-1} (Devol, unpublished data). Similarly, benthic oxygen fluxes on the Washington continental shelf during the summer are typically about -12 mmoles O_2 m^{-2} d^{-1} (Devol and Christensen, 1993). At least some of the difference between Budd Inlet and the other two areas can be ascribed to depth and temperature. At both the Dabob Bay and Washington shelf sites, bottom water temperatures remained constant at about 8 %C throughout the year, while Budd Inlet bottom waters reached 15 %C in the summer months. Additionally, the Dabob Bay site was ~100 m deep and the Washington Shelf stations were located within the 100–200 m depth range. At these deeper stations, more of the settling organic matter was decomposed in the water column, thus leaving less to fuel benthic processes.

Silicate fluxes were similar to oxygen fluxes in that they were largely reflected of the seasonal phytoplankton cycle. As diatom production increased and diatom tests settled to the bottom where they dissolved, silicate fluxes out of the sediments increased. In the fall and winter, diatom populations decreased and there was a resultant decrease in the silicate flux out of the sediments.

Although nitrate fluxes displayed little seasonality, the direction of the flux (into the sediments) indicates that oxygen was consumed relatively rapidly within the sediments, and the anoxic process of denitrification was important. The importance of denitrification in the sediments was confirmed by the observed N_2 flux out of the sediments (Figure 4). Ammonium is remineralized as a result of sedimentary decomposition of organic matter. As with oxygen and silicate, NH_4 fluxes increased in the summer resulting from increased input and degradation of organic matter, and decreased in the winter when production, transport, and decomposition slowed (Figure 3).

One of the main objectives of this study was to evaluate the influence of sediments on the water-column oxygen concentration. Calculated and observed summertime water-column oxygen depletion rates at Stations A, C, and D are shown in Table 1. Given an average bottom water oxygen concentration of 187 mM at Station A, and a calculated oxygen depletion rate of 2.9 µmole O_2 L^{-1} d^{-1}, the sediments would be capable of depleting all of the oxygen in the water column in 64 days. Similarly, it would take 77 and 149 days at Stations C and D, respectively, for the sediments to reduce the oxygen concentration to zero. Thus, the sediments appear to play a potentially important role in regulating water-column oxygen concentration. It is also interesting to compare observed daily oxygen depletion rates (from bottom water concentrations over time) to calculated daily oxygen depletion rates. Station A observed daily oxygen depletion rates were 2.1 µmole O_2 L^{-1} d^{-1} during the summer. This decrease reflects both sediment and water-column respiration, as well as an oxygen replenishment from horizontal exchange with more oxygenated water. Taking those factors into account, a calculated oxygen depletion rate of 2.9 µmole O_2 L^{-1} d^{-1} by the sediments is a significant loss term. Station C had an observed bottom water oxygen depletion rate of 1.5 µmole O_2 L^{-1} d^{-1} and a calculated oxygen depletion rate of 2.8 µmole O_2 L^{-1} d^{-1} in the summer. Similar fluxes at Stations A and C could result from the similar depth at the two stations. Station D, which was deeper, had a lower observed bottom water depletion rate (1.1 µmole O_2 L^{-1} d^{-1}) as well as a lower calculated depletion rate (1.6 µmole O_2 L^{-1} d^{-1}) than the other stations.

These calculations show that the observed bottom water oxygen depletion rate is higher, resulting in a faster depletion time, in the inner inlet where the sediments are slightly shallower and there is less contact with oxygenated water from Puget Sound. Since the calculated oxygen depletion rates also generally increase further toward the inner inlet, this suggests that the sediments in the inner inlet exert a greater relative influence on water-column oxygen concentrations than those in the outer inlet.

Table 1. Annual average bottom water oxygen concentrations and summertime oxygen depletion calculations. Calculated O_2 depletion rates were determined by dividing the summertime (May–August) average measured flux (mmoles O_2 m^{-2} d^{-1}) by the MLLW depth (m). Observed bottom water depletion rates were calculated from the observed bottom water concentration change over the same time interval. Calculated O_2 depletion time was, thus, the average bottom water O_2 concentration (µM) divided by the calculated O_2 depletion rate (µmole O_2 L^{-1} d^{-1}). Comparable calculations could not be made for Station B since it is in the euphotic zone and has the additional input of oxygen directly from photosynthesis, and the additional loss due to oxygen evasion.

	Station A	Station C	Station D
Average Bottom Water O_2 Concentration (µM)	187	214	232
Calculated O_2 Depletion Rate (µmole O_2 L^{-1} d^{-1})	2.9	2.8	1.6
Observed Bottom Water O_2 Depletion Rate (µmole O_2 L^{-1} d^{-1})	2.1	1.5	1.1
Calculated Bottom Water O_2 Depletion Time (days)	64	77	149

The second objective of this study was to evaluate the role of sediments in nitrogen cycling in the inlet. Due to the importance of nitrogen as the limiting nutrient for phytoplankton, and to potential future anthropogenic influences, it is essential to understand what sources and sinks contribute to the nitrogen budget in order to develop alternative wastewater management plans. Nitrogen sources to and sinks within the sediments in the inner and the whole inlet are shown in Table 2. In order to evaluate the importance of the sediments to nitrogen loading, we compared NH_4, NO_3, and N_2 fluxes to the total nitrogen loading to the inlet. Total inputs included inputs from Puget Sound, Capitol Lake, LOTT (Lacey-Olympia-Tumwater-Thurston County sewage treatment facility), other waste water treatment plants, sediments, streams, and rainfall (Cox and Giles, 1998).

Table 2. Annual nitrogen sources and sinks in Budd Inlet. The inner inlet is defined as from the head to Station B and includes mean data from Stations A and B. The whole inlet includes data from all stations. Yearly NH_4, NO_3, and N_2 fluxes were calculated by multiplying the average flux at each station by the respective surface area of each inlet section and then by 365 days to convert to a yearly value. All values are given in metric tons y^{-1} (mt y^{-1}) Total N loading consists of all measured nitrogen inputs to the inlet, including Puget Sound, Capitol Lake, LOTT (Lacey-Olympia-Tumwater-Thurston County sewage treatment facility), other wastewater treatment plants, sediments, streams, and rainfall (Cox and Giles, 1998). The NH_4 % of Total is the annual percentage of the total N loading attributed to NH_4 flux from the sediments.

	Surface Area (m^2)	Total N Loading mt yr^{-1}	NH_4 Flux mt yr^{-1}	NH_4 % of Total	NO_3 Flux mt yr^{-1}	N_2 Flux mt yr^{-1}
Inner Inlet	3.9×10^6	1980	101	5	-18	-61
Whole Inlet	2.0×10^7	3350	395	12	-69	-346

Ammonium fluxes comprised the only significant contribution of the sediments to the inlet, averaging 12% of the total nitrogen loading to the whole inlet. Nitrate fluxes into the sediments and nitrogen gas fluxes out of the sediments, which eventually result in N_2 being lost to the atmosphere, were both sinks attributed to the sediments. (Note, however, that the NO_3 flux into the sediments is converted to N_2 by denitrification, so it is a component of the N_2 flux out). Nitrogen gas flux values were on the same order as ammonium fluxes, signifying the importance of denitrification in the inlet. Similarly, on the Washington Shelf NH_4 fluxes were comparable to N_2 fluxes (Devol and Christensen, 1993).

Remembering that the NH_4 flux out of the sediments represents recycling and that the N_2 flux represents loss, the sediments appear to be responsible for cycling about 22% of the nitrogen loading to the inlet [(395+346)/3350].

In summary, this study strongly suggests that the sediments play an important role in the biogeochemical processes of Budd Inlet. Benthic oxygen fluxes in Budd Inlet were higher than fluxes found in other regional studies, probably due to Budd Inlet's shallower depths and the higher temperatures. Given the measured oxygen flux values, and the observed bottom water oxygen depletion rates, the sediments appear to be important in regulating water-column oxygen concentration, especially toward the head of the inlet. Similarly, benthic fluxes of various nitrogen species appear to play a significant role in the nitrogen cycling in Budd Inlet. Ammonium fluxes from the sediments to the overlying water in the whole inlet comprised 12% of the total annual nitrogen loading. Denitrification within the sediments, which was on the same order (but in the opposite direction) of NH_4 fluxes, was also a significant nitrogen sink in the inlet.

Acknowledgments

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